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Title: Impact Damage Detection of Toughened CFRP Laminates with Time Domain Reflectometry

Researcher:

Professor Akira Todoroki
Department of Mechanical Sciences and Engineering
Tokyo Institute of Technology (I1-58)
2-12-1, O-okayama, Meguro, Tokyo, 1528552, Japan
TEL/FAX: +81-3-5734-3178
E-mail: atodorok@ginza.mes.titech.ac.jp

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Abstract

Laminated Carbon Fiber Reinforced Polymer (CFRP) composites are very effective in weight saving in aeronautical structural components. For these laminated CFRP structures, it is, however, difficult to detect damage such as delamination, matrix cracks, and local fiber breakages caused by low velocity impact loading In the previous study in 2009, Time Domain Reflectometry (TDR) method was applied to a unidirectional laminated CFRP structure for the first time. In the previous study in2010, the research has been done on the application of the TDR method for the CFRP laminates. In the present study, therefore, actual impact damage is employed instead for the TDR. Electrical contact between fiber fragments exists in these micro-buckling although the electrical resistance becomes very high at the micro-buckling point. We have to investigate the applicability of the TDR method for the impact damage. A low speed impact test is performed to a cross-ply CFRP plate, and impact damage is made at the surface of the CFRP plate. TDR is applied to the cross-ply CFRP plate. The result shows that the reflected signal can be observed after the impact test. This result indicates that the TDR method is useful for detection of the low speed impact damages.

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14. ABSTRACT
Laminated Carbon Fiber Reinforced Polymer (CFRP) composites are very effective in weight saving in aeronautical structural components. It is, however, difficult to detect damage such as delamination, matrix cracks, and local fiber breakages caused by low velocity impact loading. In the previous study in 2009, Time Domain Reflectometry (TDR) method was applied to a unidirectional laminated CFRP structure for the first time. In 2010, the research applied the TDR method for the CFRP laminates. In the present study, therefore, actual impact damage is employed instead for the TDR. Electrical contact between fiber fragments exists in these micro-buckling regions although the electrical resistance becomes very high at the micro-buckling point. We have to investigate the applicability of the TDR method for the impact damage. A low speed impact test is performed to a cross-ply CFRP plate, and impact damage is made at the surface of the CFRP plate. TDR is applied to the cross-ply CFRP plate. The result shows that the reflected signal can be observed after the impact test. This result indicates that the TDR method is useful for detection of the low speed impact damages.

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1. Introduction

Laminated Carbon Fiber Reinforced Polymer (CFRP) composites are very effective in weight saving in aeronautical structural components. For these laminated CFRP structures, it is, however, difficult to detect damage such as delamination, matrix cracks, and local fiber breakages caused by low velocity impact loading because these damages are difficult to detect for visual inspection from the outside of the structure. This difficulty of inspection of the laminated CFRP structures demands the development of automatic monitoring or damage detection systems.

For the CFRP composites, carbon fibers are adopted as reinforcements, and the carbon fibers are excellent electric conductors. The carbon fiber has been used as a strain sensor for decades [1]. Recently, electrical resistance change measurement has been employed to detect and/or monitor internal damage to CFRP laminates by many researchers [2-10]. Electrical resistance change measurement does not require expensive instruments. Since the method adopts the carbon fiber itself as a sensor, it does not cause a reduction in strength, and can be applied to existing CFRP structures. Further, measurement requires no additional research to fabricate composite structures, as it does not require embedded sensors.

Although electrical resistance change measurement has advantages over other methods of structural health monitoring, it has received little attention until recent years. This is because the strong anisotropic electrical resistance of CFRP causes complicated behavior in electrical resistance change when it is measured by conventional methods. Recent research has shed light on many of the problems in this area and enabled identification of damage location and dimension by measurement of electrical resistance change at multiple points within target CFRP structures [11-18].

The electrical resistance change method, however, requires a lot of electrodes on the target CFRP structures to measure electrical resistance change of multiple segments. These electrodes are made using an electrical copper plating method. Although the portable type machines have already commercially available, to make a lot of electrodes on the target CFRP structure is tiresome.

In the previous study in 2009, Time Domain Reflectometry (TDR) method was applied to a unidirectional laminated CFRP structure for the first time. Several methods to make an electrode were tried and copper plating at the end of the CFRP structure was adopted. As the time difference between the input pulse and the reflected pulse is very small because of the short dimension of the actual CFRP structures, information techniques such as a pulse compression technique was found to be useless. As the attenuation of the electric pulse was large because of the high electrical resistance of CFRP compared with copper wire, four meters of the pulse transmission length was the maximum to detect the reflected electric pulse. In the first year research, carbon-fiber breakages made by drill holes were successfully detected.

In the previous study in2010, the research has been done on the application of the TDR method for the CFRP laminates. On the basis of the results of the previous study, the research focuses on the effect of the width of the CFRP on the TDR method to detect a small notch. Tough CFRP laminates with rubber particles between plies and normal CFRP laminates were adopted as specimens. Finite-Difference Time-Domain (FDTD) simulation method was used to visualize the effect of the two types of the CFRP. The tough CFRP laminates have very small electric conductivity in the transverse and the thickness directions compared with the normal CFRP laminates. The FDTD simulation revealed the array of electrodes enables us to detect location in the transverse direction for the tough CFRP.

In these previous studies, damages of fiber breakages were modeled using mechanical notches. In the present study, therefore, actual impact damage is employed instead for the TDR. Figure 1 shows the impact damage of toughed CFRP laminates. Figure 1 shows the fiber breakages found at the damaged point. Compression loading of the surface layer causes the fiber micro-buckling. The compression damage research [19] revealed that the fiber micro buckling did not cause electrical insulation because of the contact between fiber fragments. Figure 2 shows the fiber micro-buckling of compression loading. As shown in Fig.2, electrical contact between fiber fragments exists in these micro-buckling although the electrical resistance becomes very high at the micro-buckling point.

Fig.1 Impact damage

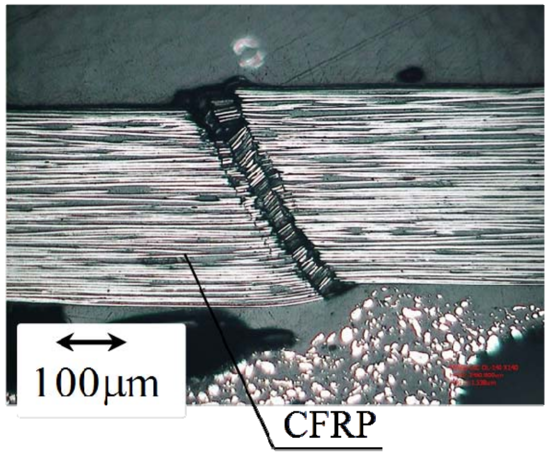

Fig.2 Fiber micro-buckling caused by compression loading

In the present study, an actual impact loading test is performed and the TDR method is applied to detect the impact damage.

2.TDR with micro-strip lines

The TDR method uses a pulse signal in a transmission line. The reflected pulse signal from the transmission line is measured and the result is observed in a figure in which the abscissa is time and the ordinate is the voltage (see Fig.3). The TDR method requires a wave generator, an oscilloscope, and a target cable, as shown in Fig. 3. The wave generator produces a pulse wave signal, which is sent in the directional coupler. The signal propagates only into the target cable because of the directional coupler. Part of the signal is reflected at the input end of the cable because of the slight difference of the characteristic impedance. The other signal propagates in the target cable. The signal input in the target cable is divided into the reflection and transmission at the damaged point. The reflected signal returns back and measured at the oscilloscope. The time difference between the input signal and reflected signal indicates the distance to the damaged point after multiplication by the speed. Using the TDR method, the damage and its location can be measured. The distance L from the input end to the damage is calculated using equation [20].

$$L = \frac{V_p \Delta T}{2} \tag{1}$$

In that equation, V_p is the transmission velocity; ΔT denotes the time difference between the input signal and the reflected signal. The transmission velocity V_p , which is affected by the transmission line, is slightly lower (approximately 0.6–0.9) than the velocity of light. For this study, the cable is replaced by a CFRP plate.

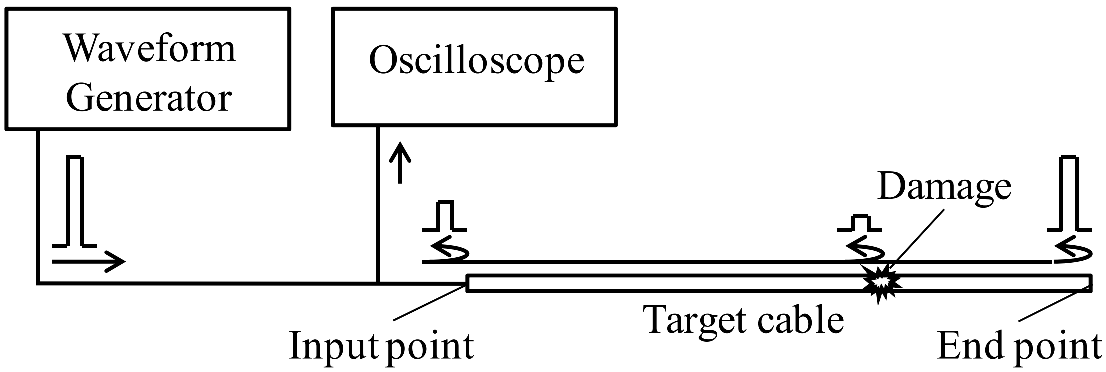

Fig. 3　Schematic representation of TDR method

When the cable is simply replaced by a CFRP plate, the characteristic impedance of the CFRP plate differs greatly from that of the coaxial cable used to connect the wave generator and the oscilloscope. This arrangement causes perfect reflection at the input end of the CFRP plate. Therefore, the pulse signal does not propagate in the CFRP plate. This makes a failure of the self-sensing TDR for the CFRP plate. The impedance matching process is, therefore, indispensable for the self-sensing TDR method of the CFRP plate. The previous study adopts an impedance matching method using a parallel aluminum plate. In the previous papers, fiber breakage damage can be detected using the parallel-plate-transmission line. Although the parallel plate method is very effective, the method, however, could not detect the location in the transverse direction, and the parallel-plate to construct the impedance matching with the coaxial cable is cumbersome for actual CFRP structures.

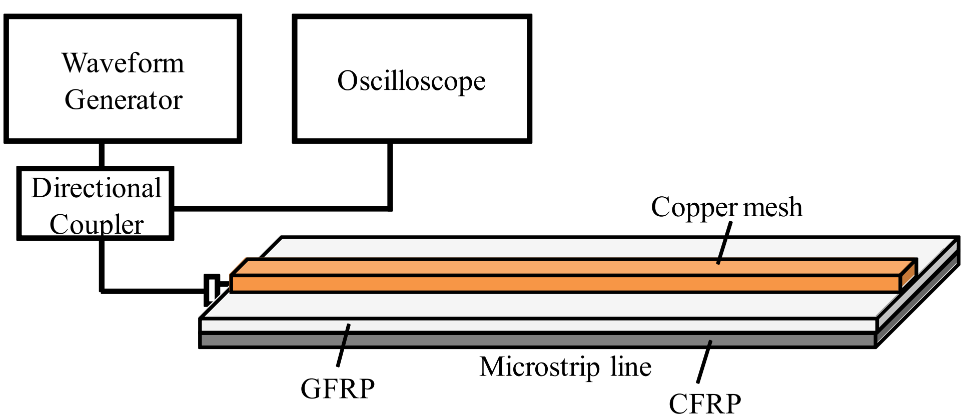

Fig.4 Schema of principle of self-sensing　micro-strip line TDR method.

In the present study, therefore, a narrow-copper-mesh strip is adopted as a transmission line as shown in Fig. 4. Usually, copper mesh is adopted as an anti-lightning method for aircraft composite structures. On the surface of a target CFRP plate, a thin GFRP plate is stacked as dielectric material, and a narrow copper strip is placed at the middle of the plate on the thin GFRP plate. The narrow copper mesh strip and the CFRP plate with the GFRP dielectric material make a transmission line with the CFRP plate. The characteristic impedance of the narrow-strip transmission line is obtained as follows [21].

$$Z_c = \frac{Z_c^a}{\sqrt{\varepsilon_W}} \tag{2}$$

$$Z_c^a = 30 \ln \left[1 + \frac{4h}{W_0} \left\{ \frac{8h}{W_0} + \sqrt{\left(\frac{8h}{W_0} \right)^2 + \pi^2} \right\} \right]$$

$$W_0 = W + \frac{t}{\pi} \ln \frac{4e}{\left[\left(\frac{t}{h} \right)^2 + \frac{1}{\pi^2 \left(\frac{W}{t} + 1.1 \right)^2} \right]^{\frac{1}{2}}}$$

$$\varepsilon_W = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + \frac{10h}{W} \right)^{\frac{1}{2}} - \frac{\varepsilon_r - 1}{4.6} \frac{t}{h} \sqrt{\frac{h}{W}}$$

where h is the height of the dielectric GFRP, t is the thickness of the strip conductive material, W is the width of the strip conductive material, ε_r is the relative permittivity of the GFRP, Z_c^a is the characteristic impedance when the dielectric material is vacuum and ε_W is effective value of relative permittivity. Using the Eqs.(2), the characteristic impedance of the narrow strip transmission line can be designed to match with the impedance of a coaxial cable of 50 Ω. Without the impedance matching, the input pulse signal is entirely reflected at the input end of the specimen transmission line. The impedance matching is indispensable procedure for the self-sensing TDR method to detect damage of the CFRP structures.

3. Experiments

Material used for the experiments is IM600/133 highly toughened CFRP prepreg produced by Toho Tenux Co. Ltd. The long specimen shown in Fig. 5 is made from the prepreg. The cure condition is 180°C×0.7MPa×2h. The specimen's stacking sequence is $[0/90_2/0]_T$. As the thickness of the specimen is very small (0.5mm), GFRP plate of 3 mm thickness is bonded to the specimen. Copper plating was used to make better electric contact at the edge. To make impact damage to the specimen, an impact test of drop weight type was used here. The drop weight type testing system is shown in Fig.6. The diameter of the impactor is 14 mm. The impact energy is 14.1 J here.

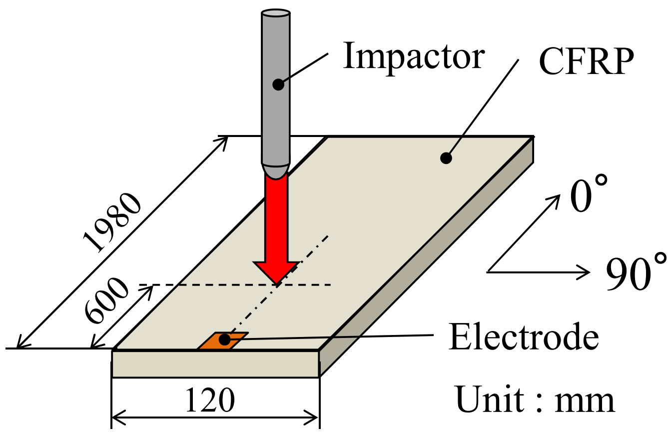

Fig.5 Specimen configuration for impact damage test

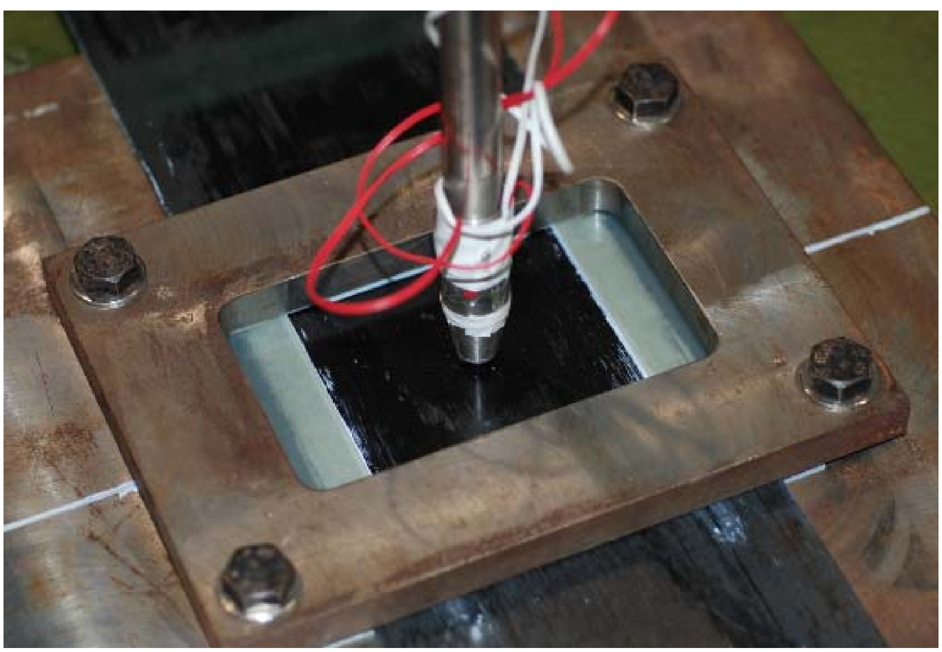

Fig.6 Photo of specimen grip and impactor for the impact test.

Copper mesh is usually used as a lightning protection system for commercial aircraft CFRP structures. The copper mesh is generally attached on a wide surface of the aircraft wing or fuselage. In the present study, a single narrow copper-mesh-strip transmission line was adopted to prevent interaction between the adjacent narrow-copper-strip-transmission lines.

To make a transmission line of electromagnetic waves, two conductive materials and one sandwiched dielectric material are required. For the dielectric material, GFRP of relative permittivity $\varepsilon_r = 4$ was adopted here; the dimensions of the GFRP plate were the same as those of the CFRP plate except for the thickness. The thickness of the GFRP was one of the design variables for impedance matching. Using Eq. (2), the copper mesh of 4 mm width is adopted here, and thickness of GFRP is 2mm. The characteristic impedance of the specimen was calculated using Eq. (2) , and that is close to 50 Ω (48.8Ω) here.

As shown in Fig. 4, a wave generator, digital oscilloscope and directional coupler were connected. The wave generator used was an AFG3251 (1 ch, Max 240 MHz) function generator manufactured by Tektronix (Tokyo Japan). The digital oscilloscope used was a TDS5034B (sampling speed of 0.01 ns) manufactured by Tektronix. The directional coupler was a ZFDC-10-5 manufactured by Mini-Circuits (N.Y., USA). The input pulse was 5 Vp-p (peak-to-peak voltage) and the half-band width was 4 ns.

4. Results and discussion

Figure 7 shows the impact damage of the specimen. As shown in the Fig.7, a small dent can be observed on the impact surface. Measured impulse signals are shown in Fig.8. The ordinate is the voltage and the abscissa is the time. The red curve shows the measured signal after the impact test and the blue curve shows the measured signal before the impact test.

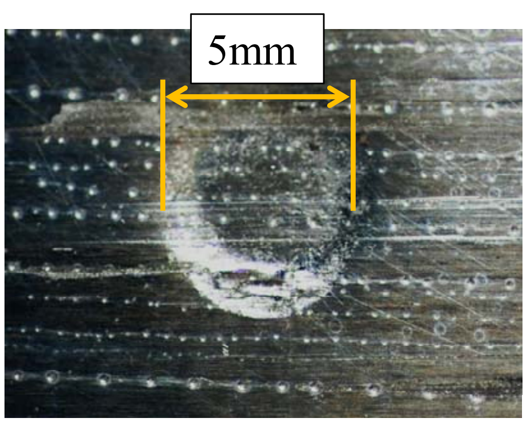

Fig. 7 Impact damage of the specimen surface

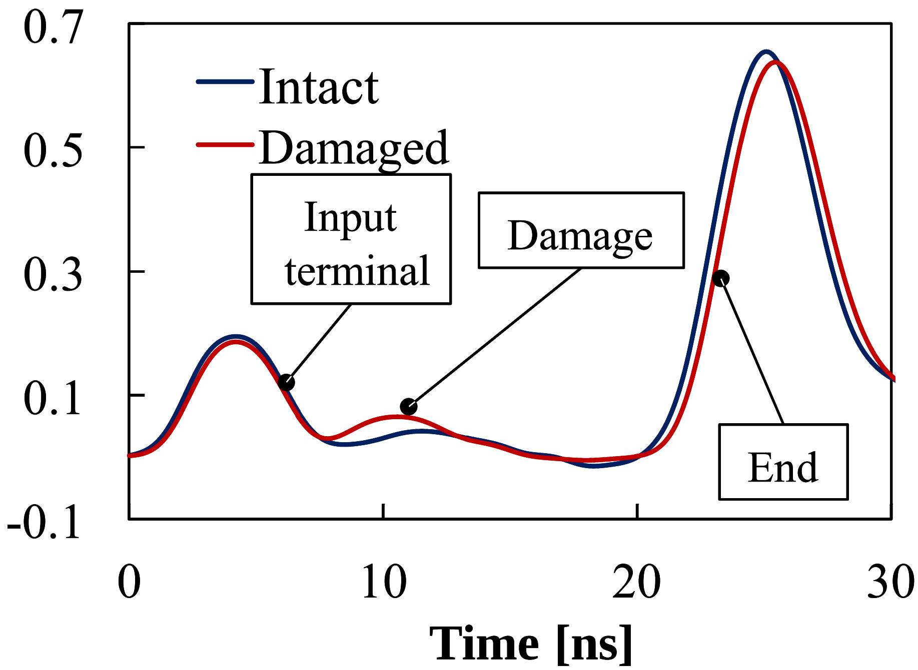

Fig.8 Measured impulse signal after the impact test

As shown in Fig.8, the reflected signal from the impact damage is observed at approximately 10 ns. The wave speed can be calculated from the time difference between the input time and the reflected signal from the end. Using the wave speed, the location of the damaged point can be calculated. The calculated damaged point is 0.58m from the input end terminal. The actual damaged point is 0.6 m. This indicates the method gives good estimation of the impact damage of a composite plate.

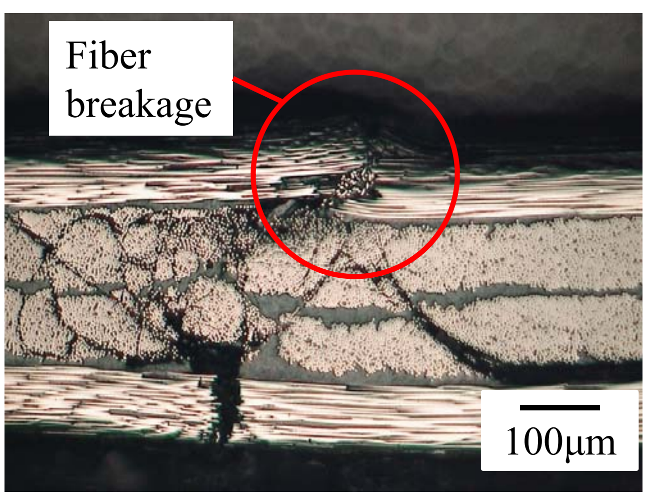

Fig.9 Cross sectional view of the impact loaded point

Cross sectional view of the impacted point was observed. Figure 9 shows the results of the cross sectional view. As shown in Fig.9, the fiber breakages are observed at the dent area because of the fiber micro-buckling. Although the fiber breakages have fiber contact as shown in Fig.9, the sudden change of the electric conductance caused the reflection of the impulse signal as shown in Fig.8. This result implies that the TDR method is useful for the detection of actual impact damage of CFRP structures.

5. Conclusions

A low speed impact test is performed to a cross-ply CFRP plate, and impact damage is made at the surface of the cross-ply CFRP plate. TDR is applied to the cross-ply CFRP plate. The result shows that the reflected signal can be observed after the impact test. From the reflected signal, the location of the impact damage is detected although the impact damage has fiber contact. This result indicates that the TDR method is useful for detection of the low speed impact damages.

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